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PRODUCTION OF HIGH-STRENGTH Mn-Ni-Al BRONZES BY THERMOMECHANICAL TREATMENTS

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PRODUCTION OF HIGH-STRENGTH Mn-Ni-Al BRONZES BY THERMOMECHANICAL
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ABSTRACT

Swaging concast Mn-Ni-Al bronzes (MAB) can produce yield strengths close to 900 MPa and an ultimate tensile strength in excess of 900 MPa. However, annealing at 400 to 500°C decreases strength properties by 7-22% depending on the aluminum and manganese contents. Swaging concast Ni-Al bronze (NAB) is also effective and produces high strength properties which annealing decreases by 4% only. In the annealed condition, MAB alloys are more ductile than the NAB alloys.

The tensile properties of concast, swaged, and annealed MAB alloys have been expressed in terms of the equivalent aluminum content.

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PRODUCTION DE BRONZES Mn-Ni-Al DE HAUT-RÉSISTANCE
PAR TRAITEMENTS THERMOMÉCANIQUES

par

M. Sahoo et J.R. Barry

RÉSUMÉ

L'emboutissage des bronzes Mn-Ni-Al (MAB) coulés en continu peut produire des tensions de fluage de presque 900 MPa et une résistance à la traction qui dépasse 900 MPa. Toutefois, le recuit à 400 - 500°C réduit ces propriétés de 7 à 22% dépendant de leur teneur en aluminium et en manganèse. Le fait d'emboutir les bronzes Ni-Al (NAB) coulés en continu est aussi efficace et peut produire une résistance élevée que le recuit réduit par 4% seulement. Dans l'état recuit, les alliages NAB s'avèrent plus ductiles que les alliages MAB.

La présente étude décrit les propriétés de fraction des alliages MAB coulés en continu, emboutis et recuits, en fonction de leur teneur équivalente en aluminium.

INTRODUCTION

In a previous paper it was shown that thermomechanical processing of a continuously cast Ni-Al bronze (NAB) increased the UTS by 75% and the yield strength by 255% whereas the elongation was reduced by 25%. The alloy contained 8.75% Al, 4.35% Ni, 4.47% Fe, 1.19% Mn and balance Cu (1). The object of this investigation was to examine the feasibility of obtaining very high strength in Mn-Ni-Al bronzes (MAB) by similar thermomechanical treatments.

EXPERIMENTAL PROCEDURE

MAB alloy rods, 22 mm in diam, containing 4 to 14% Mn and 7.5 to 9% Al were produced by vertical continuous casting. The chemical compositions of the rods are given in Table 1; it being noted that MAB alloys containing 11 to 14% Mn and 7.0 to 8.5% Al are included in ASTM B148 as alloy C95700.

The concast rods were swaged to produce 8 mm diam rods. Preliminary studies showed that MAB alloys work harden very fast and hence, swaging could not be done at ambient temperature. Annealing at 830°C and hot swaging were not very successful either. Thus, it was necessary to anneal the rods for 10 min at 830°C after each swaging step and in each case swaging was done in the hot condition. However, no annealing was necessary for the last three passes to reduce the diameter from 9.9 mm to 8 mm. It was noted that swaging became easier at lower Mn contents.

Hardness measurements were made to establish the isochronal and isothermal annealing behaviour of the swaged rods. The tensile properties of swaged and annealed rods were obtained from Hounsfield specimens with a gauge length of 11 mm and gauge diameter of 3 mm. In the case of concast alloys, tensile specimens were machined according to ASTM E8 with a gauge length of 51 mm and gauge diameter of 13 mm.

RESULTS AND DISCUSSION

ISOCHRONAL AND ISOTHERMAL ANNEALING

Swaged rods were aged for 3 h at temperatures in the range 100-800°C, and air cooled. Because the annealing behaviour was similar for all compositions, the results for only three compositions are shown in Fig. 1. These

data indicate that peak hardening occurs in the temperature range 200-300°C in all cases. Hardness values increase with increase in Al and Mn contents.

Isothermal annealing studies were done on the high Mn alloys (2T and 4T) at 400°C. Although peak hardness was obtained after an annealing time of 15-30 min, there was no significant drop in hardness after long annealing times (Table 2). Hardness values for various annealing times at 400 and 500°C are shown in Tables 3 to 9 for all compositions.

MECHANICAL PROPERTIES

Tensile properties of MAB alloys in the concast, swaged, and swaged and annealed conditions appear in Tables 3 to 9. For comparison, the tensile properties of the NAB alloy are shown in Table 10 for similar conditions.

Mechanical properties of the NAB alloys are known to be a function of aluminum content only (2,3). However, in the case of MAB alloys, manganese also has an effect on microstructures and mechanical properties which, as has been shown earlier can be expressed as an "equivalent aluminum content" i.e., $Al + \frac{Mn}{6} \%$ (4). Thus, 1% Mn is equivalent to about 0.15% Al.

Tensile properties of both concast and swaged MAB alloys are plotted in Fig. 2 to 4 as a function of equivalent aluminum content. Equivalent aluminum contents for the various compositions are given in Table 1. For each specimen condition, it is seen that UTS and YS increase and per cent elongation decreases as the equivalent aluminum content increases. The per cent increase that swaging induces in both UTS and YS diminishes as the equivalent aluminum content increases. As Fig. 5 shows, it is evident that swaging has a more significant influence on the yield strength than the UTS. No such relationship was observed for elongation. The straight lines in Figs. 2 to 5 were determined by regression analysis.

The tensile properties of concast NAB alloy fit into the equivalent aluminum plots of Fig. 2 to 5. Following swaging, which was carried out without intermittent annealing, the tensile properties are similar to those of the MAB alloy 2T with the highest equivalent aluminum content (8.95 vs 10.73).

Annealing of swaged MAB alloys produces a gradual decrease in UTS and YS and an increase in % elongation. By contrast, the UTS and YS of swaged NAB alloy increases by about 10% following annealing at 400°C for 6 h.

In fully annealed (500°C, 3 h) MAB alloys, the UTS increases with equivalent aluminum content (Fig. 2), the yield strength is independent

(Fig. 3), whereas the % elongation increases with equivalent aluminum content up to a value of 10 and then decreases (Fig. 4). In the fully annealed condition, NAB alloy exhibits very high UTS and YS and relatively low elongation (Table 10).

MICROSTRUCTURE

Optical micrographs of the 6 and 11% MAB alloys in the concast, swaged, and swaged and annealed (3 h at 500°C) conditions are shown in Fig. 6 and 7 respectively. At higher Mn contents, the volume fraction of the β phase (dark etching) increases and a finer and well-developed martensitic structure is produced. The large propeller-shaped particles in Fig. 7a are thought to be iron-rich and were found to be present only in the high-Mn alloys. Swaging and annealing produces elongated grains. Low-Mn alloys are characterized by a banded structure with many striations in the swaged or annealed conditions. Dislocation substructures in these alloys will be examined later by thin foil transmission electron microscopy.

CONCLUSIONS

1. Intermittent annealing at high temperature was necessary to swage the MAB alloys. These alloys work harden faster at high Mn contents.
2. UTS, 0.2% yield strength and elongation properties of the concast, swaged, and swaged and annealed alloys can be expressed in terms of an "equivalent aluminum content" ($Al + \frac{Mn}{6}$ %).
3. Swaging causes significant increases in yield strength, especially at low Mn contents.
4. The rate of increase in strength during swaging increases as the Mn content and the equivalent aluminum content decreases.
5. Annealing at 500°C increases elongation and reduces the yield and ultimate tensile strengths of swaged alloys. Despite this, the strength of swaged and annealed material is higher than that of concast material.

6. In the annealed condition, the tensile properties of MAB alloys are lower than those of the NAB alloys. This is probably because of the type of dislocation substructure produced after swaging and annealing. Thin foil transmission electron microscopy will be done to analyse the dislocation substructure of both the NAB and MAB alloys.

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Table 1. Chemical compositions of continuously cast Mn-Ni-Al bronze alloys.

Specimen No.	Composition ^a , wt %				Equivalent Aluminum Content $Al + \frac{Mn}{6}$ %
	Mn	Al	Ni	Fe	
2T	13.40	8.50	1.99	2.96	10.73
4T	11.10	8.20	1.98	3.32	10.05
6T	9.57	8.83	2.04	2.82	10.42
8T	7.20	9.06	2.01	3.20	10.26
21-2	6.20	8.60	1.94	3.09	9.63
21-1	5.12	8.04	2.08	3.09	8.89
21-3	4.20	8.64	1.93	3.03	9.34

^a Balance Cu.

Table 2. Isothermal aging at 400°C of swaged MAB alloys.

Specimen No.	Hardness (HRC) at aging times (h) of									
	0	0.25	0.5	1	3	7	16	24	30	48
2T	34	38.0	36.4	37	31.7	34.8	33.4	32.3	30.4	33.7
4T	31	32.4	34.1	32.6	28.7	30.7	30.0	30.2	28.9	29.9

Table 3. Mechanical properties of thermomechanical processed concast MAB alloy #2T (8.5% Al, 13.4% Mn, 1.99% Ni, 2.96% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	El % $\sqrt[4]{\text{area}}$	%RA*	Hardness HRC
concast	865	544	19	-	20.5 (100HRB)
swaged	1077	1017	4	8	34.0
swaged + 400°C, 0.5 h	1033	978	6	9	36.4
swaged + 400°C, 3 h	1054	1006	5	7	31.7
swaged + 400°C, 24 h	951	854	6	10	32.3
swaged + 500°C, 3 h	909	806	9	18	27.4
swaged + 500°C, 6 h	903	772	12	23	19.8

* Reduction in area

Table 4. Mechanical properties of thermomechanically processed concast MAB alloy #4T (8.2% Al, 11.1% Mn, 1.98% Ni, 3.32% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	El % $\sqrt[4]{\text{area}}$	%RA	Hardness HRC
concast	787	478	28	-	20.5 (98HRB)
swaged	1016	975	7	22	31
swaged + 400°C, 0.5 h	1040	958	7	12	34.1
swaged + 400°C, 3 h	992	916	10	23	28.7
swaged + 400°C, 24 h	896	799	14	32	30.2
swaged + 500°C, 3 h	841	723	20	44	25.5
swaged + 500°C, 6 h	841	710	23	44	23.4

Table 5. Mechanical properties of thermomechanical processed concast MAB alloy #6T (8.83% Al, 9.57% Mn, 2.04% Ni, 2.82% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	El % $\frac{1}{4} \sqrt{\text{area}}$	%RA	Hardness HRC
concast	785	459	18	-	19.5 (98.7HRB)
swaged	1030	992	7	13	31
swaged + 400°C, 0.5 h	992	923	10	24	34.0
swaged + 400°C, 3 h	992	916	10	23	31.2
swaged + 400°C, 24 h	923	792	13	25	31.3
swaged + 500°C, 3 h	889	758	16	34	28.2
swaged + 500°C, 6 h	875	737	15	32	25.6

Table 6. Mechanical properties of thermomechanically processed concast MAB alloy #8T (9.06% Al, 7.2% Mn, 2.01% Ni, 3.2% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	El % $\frac{1}{4} \sqrt{\text{area}}$	%RA	Hardness HRC
concast	787	442	23	-	20.5 (98.8HRB)
swaged	1006	964	14	40	28.3
swaged + 400°C, 0.5 h	958	903	12	35	33.0
swaged + 400°C, 3 h	985	930	12	36	33.5
swaged + 400°C, 24 h	965	896	11	29	32.6
swaged + 500°C, 3 h	896	806	16	36	29.0
swaged + 500°C, 6 h	889	792	17	38	24.6

Table 7. Mechanical properties of thermomechanical processed concast
MAB alloy #21-1 (8.04% Al, 5.12% Mn, 2.08% Ni, 3.09% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	El % $\frac{4}{\sqrt{\text{area}}}$	%RA	Hardness HRC
concast	612	310	44	-	81.6 (HRB)
swaged	926	896	10	29	23.6
swaged + 400°C, 0.5 h	903	868	11	33	25.4
swaged + 400°C, 3 h	909	865	12	35	24.9
swaged + 400°C, 24 h	933	900	13	37	24.5
swaged + 500°C, 3 h	863	808	15	41	23.1
swaged + 500°C, 6 h	835	754	17	49	22.6

Table 8. Mechanical properties of thermomechanically processed concast
MAB alloy #21-2 (8.6% Al, 6.2% Mn, 1.94% Ni, 3.09% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	El % $\frac{4}{\sqrt{\text{area}}}$	%RA	Hardness HRC
concast	724	415	24	-	91.6 (HRB)
swaged	1025	940	11	30	24.3
swaged + 400°C, 0.5 h	1012	941	8	20	29.2
swaged + 400°C, 3 h	993	927	12	33	29.1
swaged + 400°C, 24 h	938	876	12	31	27.7
swaged + 500°C, 3 h	882	784	18	53	25.3
swaged + 500°C, 6 h	843	719	21	53	21.8

Table 9. Mechanical properties of thermomechanically processed concast MAB alloy #21-3 (8.64% Al, 4.2% Mn, 1.93% Ni, 3.03% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	E1 % $4 \sqrt{\text{area}}$	%RA	Hardness HRC
concast	624	307	31	-	82.2 (HRB)
swaged	939	892	9	25	22.4
swaged + 400°C, 0.5 h	948	898	8	25	24.9
swaged + 400°C, 3 h	900	841	8	23	26.0
swaged + 400°C, 24 h	879	841	11	33	24.8
swaged + 500°C, 3 h	852	787	17	44	22.0
swaged + 500°C, 6 h	816	730	16	42	21.3

Table 10. Mechanical properties of thermomechanically processed concast MAB alloy #12-2 (8.75% Al, 1.19% Mn, 4.35% Ni, 4.47% Fe).

Specimen condition	UTS MPa	0.2% YS MPa	E1 % $4 \sqrt{\text{area}}$	%RA	Hardness HRC
concast	663	313	30	-	83 (HRB)
swaged	1055	997	6	13	34
swaged + 400°C, 3 h	1155	-	-	-	37
swaged + 400°C, 6 h	1162	1107	5	8	37
swaged + 400°C, 24 h	1149	1088	8	19	37
swaged + 500°C, 3 h	1014	956	8	18	30

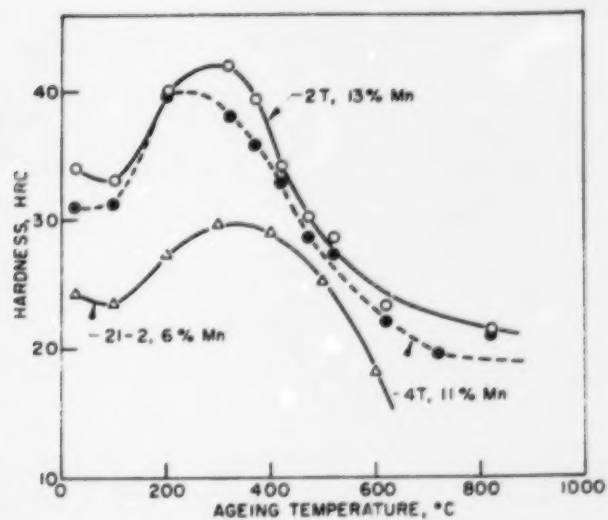


Fig. 1. Results of isochronal annealing experiments (3 h annealing time). (neg 9022)

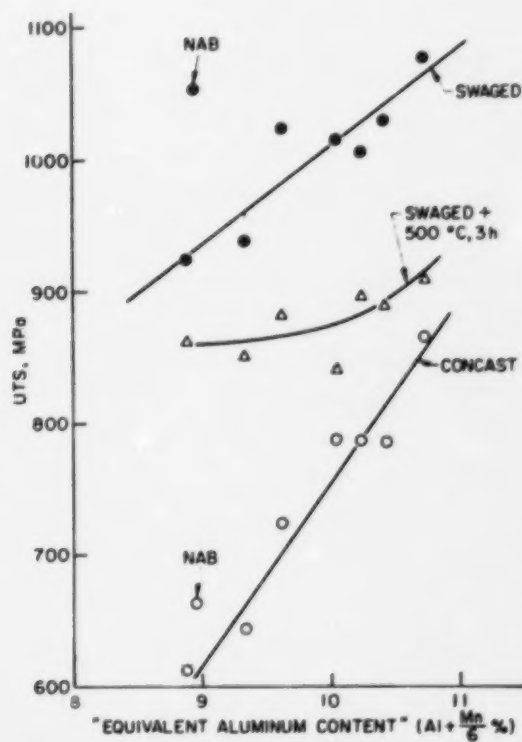


Fig. 2. Ultimate tensile strength vs "equivalent aluminum content" ($Al + \frac{Mn}{6}$ %). (neg 9024).

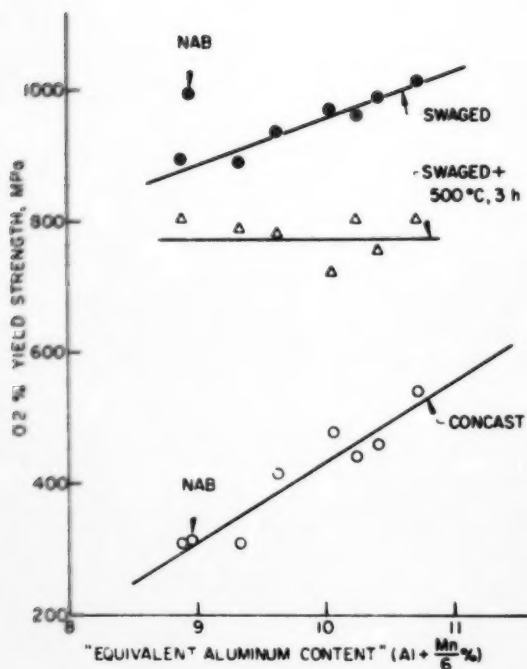


Fig. 3. 0.2% offset yield strength vs "equivalent aluminum content" $(Al + \frac{Mn}{6} \%)$. (neg 9021)

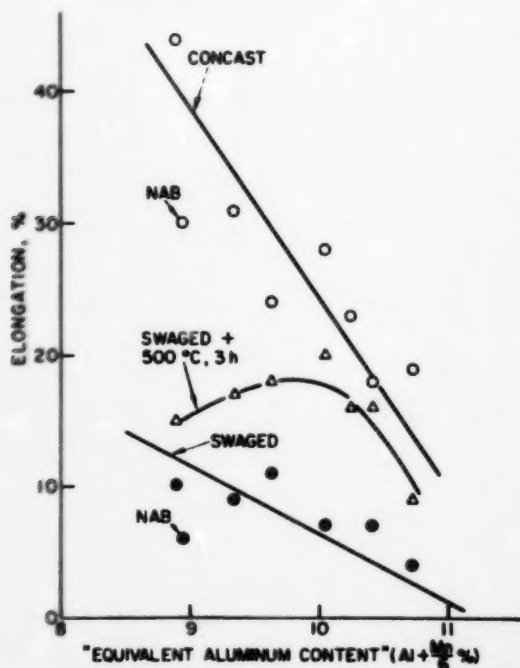


Fig. 4. Elongation vs "equivalent aluminum content" $(Al + \frac{Mn}{6} \%)$. (neg 9023)

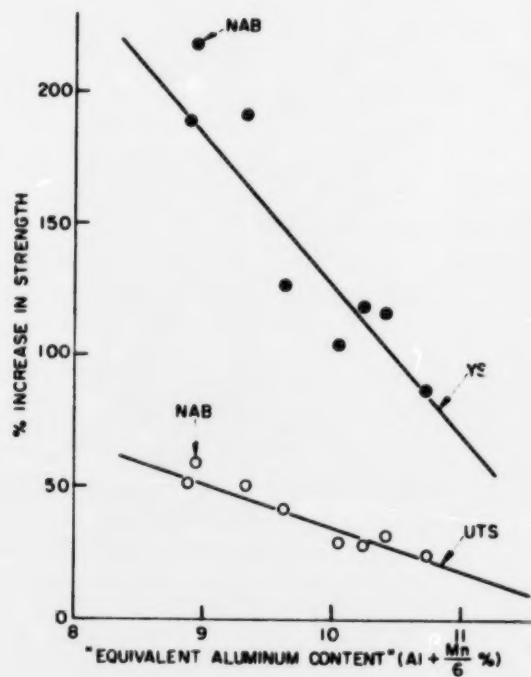


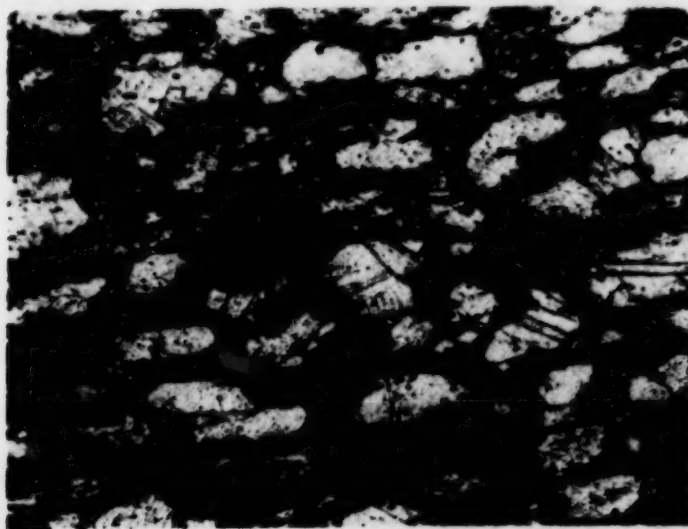
Fig. 5. % increase in strength from swaging vs "equivalent aluminum content" ($Al + \frac{Mn}{6}$ %). (neg 9025)



(a) concast (neg 7468)



(b) swaged (neg 7469)

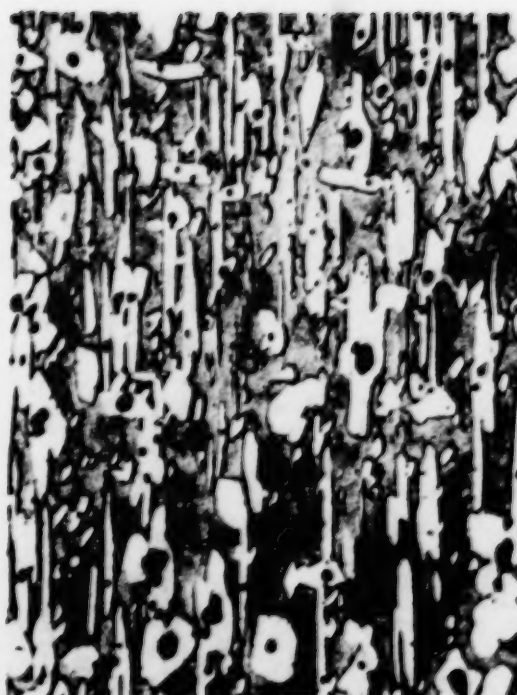


(c) swaged and annealed for 3 h at 500°C. (neg 7470)

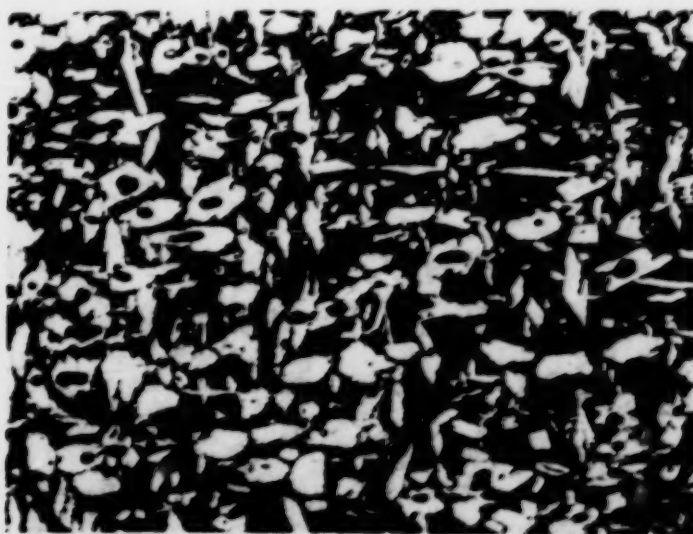
Fig. 6. Optical micrographs of alloy 21-2 containing 6.2% Mn, 8.6% Al, 1.94% Ni, 3.09% Fe and balance Cu. Alcoholic ferric chloride etch. X500



(a) concast, X500. (neg 7471)



(a) swaped, X1000. (neg 7472)



(c) swaged and annealed for 3 h at 500°C. X1000. (neg 7473)

Fig. 7. Optical micrographs of alloy 4T containing 11.1% Mn, 8.21% Al, 1.98% Ni, 3.32% Fe and balance Cu. Alcoholic ferric chloride etch.